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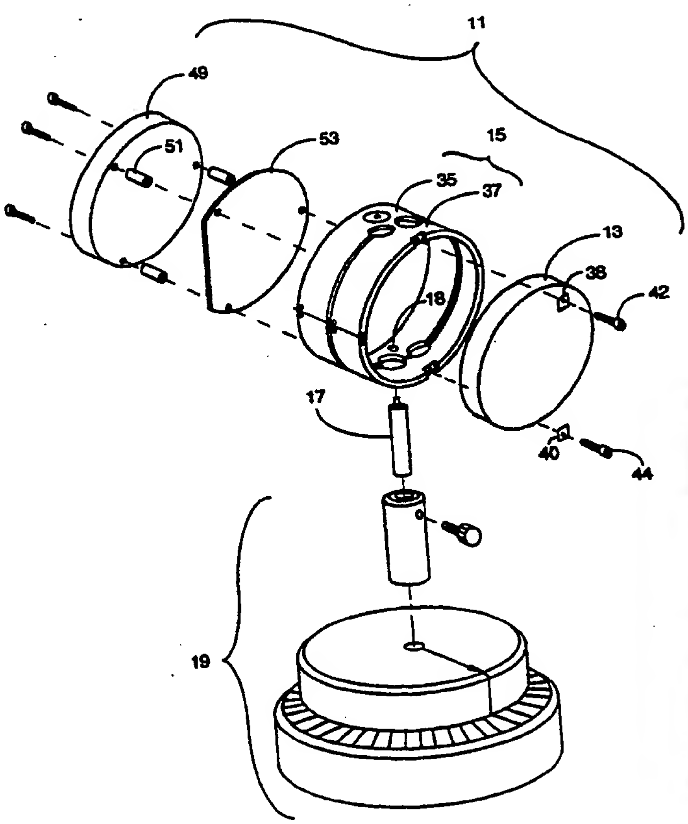
(54) Title: DYNAMIC SHEARING INTERFEROMETER

(57) Abstract

An interferometer according to the invention is made up of a shearing element (13) for amplitude division by reflection of an incident beam of electromagnetic radiation into two parts, each part having a wavefront with a direction of propagation that is substantially parallel to the other, the two parts being displaced relative to each other in a direction transverse to the direction of the incident beam so as to cause interference fringes between the two parts; and a mounting element (15) for supporting the shearing element (13) and for rotating the shearing element (13) by small amounts about an axis transverse to the incident beam. In the preferred mode, the shearing element (13) is a shearing plate with flat faces and is made of a transparent material.



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DYNAMIC SHEARING INTERFEROMETER

Cross-reference to Related Applications

This patent application is a continuation-in-part of copending application serial number 657,289, filed February 19, 1991, entitled DYNAMIC LATERAL SHEARING INTERFEROMETER, by James J. Snyder, and of copending application serial number 701,405, filed May 14, 1991, entitled DYNAMIC SHEARING INTERFEROMETER, by James J. Snyder, both of which are incorporated herein by reference.

Background of the Invention

Modern commercial interferometers from companies such as Zygo and Wyko, which are used for inspection of optics, are usually either Fizeau or Twyman-Green (Michelson) interferometers. In both types of inspection interferometers, a collimated laser beam generated within the instrument is split into two beams, one of which provides a reference surface while the other beam is passed through the test optic set up in such a way that if it were perfect the exiting beam would exactly match the wavefront of the reference beam. The two beams are combined with a beamsplitter and the resulting fringes of constant height represent a contour plot of the wavefront transmitted by the lens. The fringe pattern is captured by a two dimensional detector array (such as a CCD camera) and analyzed by computer to provide various parameters of the performance of the optic and the details of the distortion it causes. Although these instruments are well suited to measuring the quality of optical components, they are not able to directly measure the wavefront of a beam. Moreover, if the test wavefront deviates significantly from the reference wavefront, so that the fringe spacing approaches the pixel size anywhere, then the instrument is unable to correctly interpret the fringe pattern. A different type of interferometer is available from Wyko for direct measurement

of the wavefront of a nearly collimated laser beam. This interferometer is a self-referenced Mach-Zehnder with equal optical path lengths. In this interferometer, the reference beam is focussed through a pinhole spatial filter to remove all wavefront aberrations and the remaining spherical wave is collimated by a lens. The test and reference beams travel the same total distance before being recombined at a beamsplitter, so that laser sources with short coherence lengths can be utilized. The fringe pattern of the self-referenced Mach-Zehnder is essentially similar to the fringe patterns produced by the other forms of interferometers, and it is recorded and interpreted in the same way. If desired, the instrument can also be used to measure optics by measuring the wavefront of a beam from a test optic which would have produced a collimated output beam if the optic were perfect. For example, if a test lens were illuminated by a point source located at its focal point, the transmitted beam would be collimated if the lens were free of aberrations.

Instead of measuring the position of fringe extrema in the interference pattern, modern commercial interferometer systems store a sequence of interferograms, each identical except for having a different overall phase shift between the reference and the test beams. The phase shift between exposures is modified by changing the optical delay, e.g., by moving the reference mirror a fraction of a wavelength. The starting phase at each pixel, and therefore the pixel-by-pixel wavefront deviation of the test beam relative to the reference beam, can be calculated from the sequence of intensities measured at each pixel if the phase shifts are accurately known. This technique, called phase shift interferometry, offers substantially better signal-to noise ratio in the phase measurement and in addition provides a uniform grid of phase data that is independent of the number of fringes. However, it adds significantly to the

complexity and cost of the instrument because of the requirement for moving a mirror an accurately calibrated distance between exposures. The motion is generally done using piezoelectric transducers, which suffer from hysteresis effects and non-linearities, as well as being expensive to implement.

Because of their optical complexity, as well as their requirement for mechanical stability coupled with the need to scan a reference mirror, commercial interferometers are expensive (approximately $100,000.00), and require precisely controlled laboratory environments. As a result, they tend to be located in special optical testing centers where potential users bring optical components for examination.

Another kind of interferometer is the lateral shearing plate interferometer. This instrument typically consists of an uncoated glass plate with flat surfaces. Some implementations have parallel surfaces, and some have a small angle (wedge) between the surfaces.

In comparison with most other interferometers, shearing interferometers are very compact, they are self-referencing, and the interfering rays travel common or nearly common paths, so that they are relatively insensitive to alignment, vibration, or air turbulence. These features favor the use of shearing interferometers for laboratory and industrial applications.

Lateral shearing interferometers are commonly used for measuring the wavefront shape of a laser beam. If the shearing plate is wedged, the lateral shearing interferometer is sometimes referred to as a Fizeau interferometer, which, with the proper orientation of the wedge, can be used to measure the wavelength of the laser beam as well as the wavefront shape.

The shearing interferometer is placed at an angle relative to the incident beam to be characterized and two reflections of the incident beam result. One reflection is

from the front surface of the glass plate and the other is from the back surface. (Other multiple reflections also occur between the surfaces before they exit the front surface. These multiply reflected beams are, however, much lower in intensity than the two principal beams described, and hence will be ignored in the ensuing analysis.) These two reflected beams from the front and rear surfaces interfere where they overlap. For non-normal incidence light, the reflected beams are displaced transversely from each other, so that the fringe pattern in the region of overlap is due to the interference of the wavefront with a sheared version of itself. The resulting fringes of constant slope are analyzed to determine the fringe phase, which corresponds to a one-dimensional derivative of the wavefront. The wavefront shape is found by integrating the wavefront derivative along the shear direction. A screen or other plane, opaque, surface placed in the path of the reflected beams will show the transverse displacement of the optical axes of two beams, hereinafter called the lateral shear "s", which is a function of thickness of the plate, the index of refraction of the shearing plate material, and the angle of incidence. The value of the shear can be calculated directly from these parameters.

These principles of the lateral shearing interferometer are illustrated in Fig. 1B, which shows a plan view arrangement of a lateral shearing plate interferometer with a laser source 111 producing a beam 113 incident on an optic 114 under test. Beam 113 exits the optic approximately collimated but slightly diverging, and is incident on a shearing plate 115. The beam incident on the shearing plate is shown diverging to an exaggerated degree to facilitate illustration of virtual sources. The outer edges of the incident beam reflect from the front surface of the shearing plate at points 117 and 119.

The outer edges of the incident beam reflect from the

back surface at points 121 and 123. The reflected beams, partially superimposed, travel in the direction of arrow 125 away from the shearing plate, and appear to come from two different virtual sources, one at point 127 and the other at point 129. These two virtual sources have a lateral separation, s, the lateral shear, and also an axial separation, l, called the axial delay. The details of the geometry can be seen more clearly from Fig. 1B. For a shearing interferometer with index of refraction n and thickness t, the shear of the two sources produced by reflection of a beam incident at angle ϑ is given by

$$s = 2*d1*\cos\vartheta ,$$

where d1 is shown in Fig. 1B. From Snell's Law,

$$\sin\vartheta = n*d1/(t^2 + d1^2)^{1/2}$$

Solving for d1

$$d1= t*\sin\vartheta/(n^2 -\sin^2\vartheta)^{1/2}.$$

Thus the shear between the two reflected beams is

$$s = t*\sin 2\vartheta/(n^2 -\sin^2\vartheta)^{1/2}$$

Similarly, the axial delay l, is given by

$$l = 2*n*d2-d3,$$

where $d2 = n* d1/\sin\vartheta$,

and $d3 = 2*d1* \sin\vartheta$.

Hence, the axial delay is

$$l = 2t*(n^2 -\sin^2\vartheta).$$

Fig. 2 shows a theoretical superposition of the two reflected beams of Fig. 1A as they would look if they were incident on a plane surface 131 viewed in the direction of arrow 125. The beam reflected from the front surface is represented by circle 133 on surface 131 in Fig. 2 and the beam reflected from the back surface is represented by circle 135. The two beam circles are offset by the distance of the lateral shear s. Area 137 is the area of superposition and interference of the reflected beams. If the laser beam is reasonably free of aberrations and close to collimation, the interference area will show parallel

alternating light and dark bands (fringes), approximately as shown in Fig. 2, although there will be some shading from light to dark not shown in Fig. 2. (To first order, the fringe pattern is sinusoidal in intensity.) Although the above analysis is for the case of a shearing plate with parallel surfaces, those skilled in the art will realize that similar results hold for a wedged plate.

A good treatment of lateral shearing interferometry can be found in the book Optical Shop Testing, published by John Wiley and Sons, Inc. of New York, N.Y., and edited by Daniel Malacara, pages 108 through 141, incorporated herein by reference. As may be seen in the referenced publication, interferometry may be used to divine considerable information about an incident beam and any apparatus that is used to emit, transmit, or manipulate the beam. To date, however, no known lateral shearing interferometers have provided the capability for wavefront analysis that is inherent in the more expensive Fizeau or Twyman-Green interferometers.

What is needed is an inexpensive, easy-to-use, interferometer, with the capability to measure the complex amplitude (both field amplitude and field phase) profile of a laser beam wavefront, and to convert the measurement into parameters which are commonly used to characterize lasers. These parameters include beam quality characteristics, such as M^2 and Strehl ratio, which describe how well the laser beam will focus, and other parameters related to optical aberrations, such as Zernicke polynomials and Seidel aberration coefficients. The interferometer should also provide for straight-forward conventional measurement of aberrations of optical compoonents and systems.

Summary of the Invention

In accordance with preferred embodiments of the invention, a wavefront analyzing interferometer is provided that can be used either to fully characterize (i.e., measure the complex field amplitude of) a laser wavefront or to test optical components or systems, and that is robust enough to operate in a normal factory environment. The instrument is a lateral wavefront shearing phase shift interferometer. It is inherently mechanically stable and relatively inexpensive because of its simplicity. It has readily adjustable sensitivity, so that it can directly measure even steep wavefronts which produce very high fringe densities that cannot be measured using the usual commercial interferometers.

In the preferred mode, the interferometer is made up of a shearing element for amplitude division by reflection of an incident beam of electromagnetic radiation into two parts, each part having a wavefront with a direction of propagation that is substantially parallel to the other, the two parts being displaced relative to each other in a direction transverse to the direction of the incident beam so as to cause interference fringes between the two parts; and a mounting element for supporting the shearing element and for rotating the shearing element by small amounts about an axis transverse to the incident beam.

In the preferred mode, the shearing element includes a shearing plate with flat faces and is made of a transparent material. The optical delay of the interferometer is changed by rotating the shearing plate of the interferometer through a small angle relative to the incident light beam by means of the mounting element. In the preferred mode, the mounting element includes a thermally driven wire that is self-calibrated by means of its resistance so as to rotate the shearing plate relative to a portion of the mounting element via thermal expansion of the wire. The desired

phase shift is provided by the amount of rotation of the shearing plate.

Brief Description of the Drawings

Fig. 1A is a plan view of a shearing plate arranged at an angle with a laser source, an optic under test and a display surface to illustrate the principles of lateral shearing interferometry.

Fig. 1B is a cross-sectional view of the shearing plate of Fig. 1A showing the geometry of various rays of light traversing and reflecting from the shearing plate.

Fig. 2 is a view of an interference pattern produced by the arrangement of elements of Fig. 1.

Fig. 3 is an expanded view of a dynamic lateral shearing interferometer according to a preferred embodiment of the invention.

Fig. 4 is an assembled view of the interferometer of Fig. 3.

Fig. 5 shows a typical measurement setup for using the personal interferometer to characterize the wavefront of an optic under test.

Fig. 6 is a schematic of a drive system for rotating the shearing plate of the personal interferometer in a calibrated manner.

Fig. 7 is a schematic of an alternative drive system for rotating the shearing plate of the personal interferometer in a calibrated manner.

Fig. 8 is a schematic of a portion of an alternative embodiment of the invention designed to measure wavefront characteristics along two axes simultaneously.

Fig. 9 is a schematic of an interferometer system according to the invention for sequentially measuring wavefront characteristics along two axes.

Description of the Preferred Embodiments

Illustrated in Fig. 3 is an expanded view of a dynamic lateral shearing interferometer 11 which can be used for studying wavefront profiles. Interferometer 11 includes an uncoated, plane-parallel glass plate (i.e. shearing plate), hereinafter etalon 13, mounted in a ring structure 15, typically constructed of black-anodized aluminum, although other materials could also be used.

The mounting ring is partially split into a front half 37, which houses etalon 13, and a back half 35 which is attached via a threaded mounting hole 18 to an adjustable mounting post 17, such as an industry standard stainless steel 1/2 inch (1.27 cm) post. The mounting post is supported by a stable base assembly 19 that is a commercially available rotation stage. Due to the fact that the base assembly is a rotation stage, it includes angular gradations so that angular rotations of the interferometer relative to the base can be accurately measured.

As can be seen more clearly in Fig. 4, the mounting ring has been partially split by cutting through the ring in the middle along a vertical axis, with cuts 28 and 29 terminating in two pairs of stress relief drill holes 20 and 21, and 22 and 23. A saw cut of about 1/16 inch (0.16 cm) in width is preferred. The uncut regions between the pairs of drill holes form an integral pair of flexure hinges 25 and 27 located along a vertical diameter of the etalon.

The flexure hinges permit a small amount of frictionless rotation of the etalon and its mounting ring relative to the base assembly. As will be discussed subsequently, this motion can be used to change the angle of incidence of an incident beam being tested, thereby causing an associated interferometer fringe pattern to be scanned. In the preferred mode, the mounting ring is constructed of a piece of aluminum pipe, 3 inch (7.62 cm) schedule 80, 6061-T6 aluminum, having a length of about 1.375 inches (

3.5 cm). Nominally the pipe has a standard inner diameter of 2.9 inches (7.37 cm).

In order to accommodate a 3 inch diameter etalon that is 1/2 inch (1.27 cm) thick, the pipe is typically milled to provide an opening of 3.01 to 3.02 inches (7.65 to 7.67 cm) on one side that is slightly deeper than 1/2 inch (1.27 cm), 0.550 inches (1.40 cm) being preferred. This also provides a land 30 for the etalon near the middle of the pipe. The etalon is mounted in front half 37, against land 30, and is held in place by two tabs 38 and 40 held by two screws 42 and 44. Also in the preferred mode, the diameter of drill holes 20-23 is 3/8 inches (0.95 cm) with a center-to-center separation between adjacent pairs being about 0.438 inches (1.11 cm), leaving a separation between the edges of the holes of about 1/16 inches (0.16 cm) for the flexure hinges. Those skilled in the art will appreciate that these dimensions can vary considerably depending on the desired elastic constant of the flexure hinges and the materials being used for the ring.

The etalon in the preferred embodiment is nominally a 3 inch diameter by 1/2 inch thick plate of BK-7 glass. Other materials, such as fused silica may also be used. The etalon in the preferred embodiment has a flatness specification of less than or equal to Lambda/10 at 633 nanometers with a clear aperture of 3 inches. Also in the preferred mode, the residual wedge is specified at less than Lambda/10 at 633 nanometers. Those skilled in the art will appreciate that these specifications have been chosen to obtain a desired precision in determining wavefront profiles, and that other specifications would yield different measures of precision.

Shown in Fig. 5 is a typical measurement setup for using the personal interferometer 11 to determine wavefront characteristics of an optic 311 under test. The apparatus is set up so that a laser 309 provides a beam through optic

311 which is approximately collimated if the optic were free of aberrations. The personal interferometer is positioned in the beam that emerges from the optic, and the interferometer stage is rotated such that the beam is retroreflected back to the source. The rotation stage of the interferometer is then used to rotate the angle of incidence of the laser beam in order to provide a shear of the reflected beams of about 1/3 of a beam diameter. The precise angle of incidence is read off from the stage and entered into a computer 315. The user then enters the laser wavelength into the computer, which then determines the precise incremental etalon rotation needed to change the interference phase by 1/4 wave using the wavelength, the angle of incidence, and the thickness and index of refraction of the etalon. The determination of the amount of etalon rotation that is required to change the phase by 1/4 wave can be made by precalibrating the instrument or by using algorithms to analytically perform such calculations. (The calibration approach is very simple and entails illuminating the interferometer with a collimated beam, rotating the etalon so that the interference pattern is changed by one fringe and is therefore identical to what it was before rotation, and dividing the rotation angle by 4.) The user then initiates the measurement process. In doing so, a CCD camera 317 and a frame grabber 319 are used to capture one frame of video which is then stored in the computer. The etalon is then rotated about the flexure hinges by the correct amount to provide a 1/4 fringe shift in the beam reflected from the etalon. Again one frame of video is stored, and so forth until a total of four frames of video are stored. The stored video data is processed using standard algorithms to provide the starting phase and the fringe contrast (depth of modulation) of the interferogram at each pixel in the frame.

The fringe pattern intensity distribution can be

described by

$$I(x,y) \doteq A(x,y)A^*(x+s,y) = |A(x=s,y)|^2 + |A(x,y,)||A(x+s,y)|\cos\phi_f(x,y)$$

where A(x,y) is the complex field amplitude at point (x,y) and s is the shear, which is assumed to be along the x-direction. The fringe phase, $\phi_f(x,y)$, is shifted in steps of Pi/2, as described above, causing the measured intensity at each pixel to vary sinusoidally due to the last term in the equation. A sequence of four measurements can be analyzed using the Fast Fourier Transform or other algorithms, to determine the amplitude and phase of the last term in the equation.

The fringe phase is processed using standard algorithms to generate the wavefront phase, $\phi(x,y)$, at each pixel along the shear (x) direction. That phase information is then converted into a wavefront profile map which is shown on display 321. Also, as is known in the art, other parameters can be calculated as well: for example, RMS error, peak-to-valley error etc.

The fringe amplitude, $|A(x,y)||A(x+s,y)|$ at each pixel is the product of magnitudes of the field amplitudes of the two sheared beams. The fringe amplitude data along each row of pixels is processed using standard algorithms, such as least squares fitting, to determine the field magnitude $|A(x,y)|$ near the wavefront. This data, when combined with the wavefront phase at each pixel, $\phi(x,y)$, gives the full complex field distribution

$$A(x,y) = |A(x,y)|\exp(i\phi(x,y)).$$

Since the complex field amplitude fully characterizes (except for polarization) the electromagnetic field at the measurement plane, the field or intensity at other points along the propagation path can be directly calculated using basic optical principles. For example, the far field divergence of the beam or the intensity distribution at the focus of a lens can easily be calculated by Fast Fourier

Transformation and squaring of the measured complex field amplitude. The far field divergence or the focussed intensity distribution can be compared to calculated values for ideal beams in order to determine standard beam characterizations such as the beam quality (sometimes referred to as the M^2 parameter and the Strehl Ratio.

Angular motion to cause a controlled rotation by means of the flexure hinges is provided in the preferred embodiment by a ThermX (tm) translator, available from Blue Sky Research, Inc. of San Jose, CA. The ThermX translator includes a wire 31 (Fig. 4) that is connected under tension between front half 37 and back half 35 of ring structure 15. An electrical circuit, hereinafter the ThermX translator driver, including control electronics that heats the wire is contained in package 49. Although the wire is typically heated continuously to control its length, it is also continuously cooled by radiation and convection to its surrounding environment. (The ThermX translator and driver will be discussed in more detail subsequently.)

Wire 31 is connected to two threaded studs 41 and 43 (Fig. 4), which are electrically insulated from the ring and which are connected to each of two power wires 45 and 47 that lead to the ThermX translator driver mounted in package 49 to the backside of the interferometer ring structure. Driver Package 49 is separated from ring structure 15 on spacers such as spacer 51, and a thermal shield 53 is assembled between the ring and driver to prevent heat from the driver from affecting the thermal stability of the etalon. The driver package could as well be mounted elsewhere, for example another preferred mode would be in the base, but the mounting shown in Fig. 4 has the advantage of allowing the power wires to be short. The advantage of a base mounting for the driver package would be that it would permit transmission of the incident beam to occur which could be an advantage to use for high power lasers, and

would also likely have less thermal excursions of the etalon due to heating from the circuit elements.

Nuts engage the threaded studs 41 and 43, and are used to apply initial tension on the flexure hinges, which in turn compress the front and back sides of the split ring structure toward each other, so that the gap of cut 28 is decreased. The initial displacement is about 0.1 mm, which results in an initial angular displacement of the etalon of about 0.14 degrees.

When wire 31 is heated or allowed to cool, it elongates or contracts ideally in proportion to its length and its thermal expansion coefficient. Hence, front half 37 which holds the etalon rotates about the flexure hinges relative to rear half 35 through a small angle, smaller than the initial displacement angle, as necessary to achieve a rotation of 1/4 fringe per frame.

The self-contained ThermX translator driver is powered by a DC power supply (not shown). The current supplied by the power supply controls the length of the wire and causes the etalon to be displaced through a small angle about the vertical axis defined by the flexure hinges of the ring structure. This small angle displacement changes the axial delay of the light reflected from the front and back surfaces of the etalon.

Those skilled in the art will understand that the system for changing the relative separation of the front half and the back half of ring structure 15 need not be the ThermX translator, but could be also be another kind of electromechanical system. For example, one could use a stack of piezoelectric crystals or even a motor-driven screw. The ThermX translator is, however, a much simpler and more elegant implementation of a displacement system for such moderately small displacements.

ThermX Translator and Drive

As indicated earlier, the fundamental element of the ThermX drive system is resistive wire 31. The wire is specially chosen to have both a large thermal expansion coefficient and a large temperature coefficient of resistance. The wire is held under tension, and its length defines the spacing which is to be controlled. The length of the wire at a temperature T(C) is

$$L = L_0 + a_L*L*T \doteq L_0(1 + a_L*T) \quad (a_L*T << 1),$$

where L_0 is the length at 0 degrees Centigrade and a_L is the thermal expansion coefficient. The resistance of the wire is given by

$$R = R_0 + a_R*R*T \doteq R_0 \; (1 + a_R*T) \quad (a_R*T << 1)$$

where R_0 is the resistance at 0 degrees Centigrade and a_R is the temperature coefficient of resistance. These two equations can be combined to give the resistance as a function of the length

$$R \doteq R_0 \; (1 + a_R*L/a_L*L_0 \; - a_R/a_L)$$

and the change in resistance with length is given by

$$\frac{dR}{dL} = \frac{R_0 \; *a_R}{L_0*a_L}.$$

A current is passed through the wire to heat it and cause it to elongate, thereby increasing the controlled spacing. The temperature of the wire and thus its length is monitored by sensing the resistance of the wire. Since the thermal expansion and the change of resistance are highly reproducible functions of temperature, the change in resistance of the wire provides an accurate measure of the change in length of the wire. Unlike most other transducers, the ThermX wire system provides both the drive mechanism and the position sensor in the same simple element.

Shown in Fig. 6 is an electrical schematic of the ThermX drive. As it should already be clear, the ThermX drive is a precision microtranslator that is particularly

adapted for moving the etalon of the personal interferometer in very precise increments in order to carry out the calibrated phase shifts required for interferometric study of wavefront characteristics. In this preferred embodiment, a Wheatstone bridge 205 is configured from resistors R111, which is the ThermX drive resistance wire (31), and resistors R211, R311, and R411. For best results these resistances are all approximately equal, about 2 Ohms. In the preferred embodiment, the requirements for wire 31 were met using a resistance wire Stablohm 610, 36 AWG (0.005 inches diameter), having a resistivity of 24 Ohms/linear foot, and a linear expansion coefficient of 15.6 parts/million/degree C. This wire also has a thermal coefficient of resistance of 400 ppm/degree C. The requirements for resistors R211, R311 and R411 were met using a resistance wire Stablohm 800, 36 AWG, having a resistivity of 32 ohms/linear foot, and a thermal coefficient of resistance of 5ppm/degree C. These wires can be obtained from California Fine Wire Company in Grover City, California. Other wires could also be used, of course, depending on the temperature characteristics desired.

Bridge 205 is used for sensing the resistance of ThermX drive wire R111, the resistance being directly proportional to the length of the wire to first order. An AC signal from a master oscillator 209 drives the bridge via an amplifier A4, while a DC current is provided from a computer controlled power supply 217 in order to adjust the length of wire R111. A capacitor C1 is used for DC isolation. The bridge imbalance is detected by a differential amplifier A3, and a phase sensitive amplifier 213 amplifies the AC imbalance, the amplitude of which is proportional to the length of wire R111. The phase sensitive amplifier then feeds back a position signal to computer 215 which then adjusts the drive signal to power supply 217 to control the

length of the wire accordingly.

In an alternative embodiment the Wheatstone bridge balance is sensed using the DC current that heats the wire. In this alternative embodiment, the error signal is normalized by dividing by the voltage across the bridge. An example of this embodiment is shown in detail in Fig. 7. Here, the ThermX drive resistor is represented by R1, typically about 2 Ohms. R2 is the matching resistor for R1, and is also typically about 2 Ohms. The other side of the bridge is represented by resistors R3 and R4, which are typically much larger, for example both about 1K Ohm. Resistor R5 acts as a trim potentiometer, and in the this example has a resistance of about 100 Ohms. A7 is an instrumentation amplifier, i.e. it has good common mode rejection, and in this example an appropriate choice would an AD624, available from Analog Devices. DIV is a divider for normalizing the error signal. In this example, an appropriate choice for divider DIV would be an AD633, also available from Analog Devices. Typically, A1 has a gain of about 1000, and DIV a gain of about 10, and the quiescent current through the bridge is about 0.2 A. I1 is an integrator, which here is shown schematically as an operational amplifier, A8, with a capacitor C2, and a resistor R7.

In operation, V_{REF} is the driver for the V1 node. (Ostensibly, without V_{REF}, V1 and V2 would be equal, since V1 would track V2, which is set by R5.) By setting V_{REF}, the drive current through the bridge can be changed such that the ThermX resistor R1 changes its resistance so as to change the voltage V1 in a calibrated way (i.e. R1 tracks V_{REF}). DIV serves to scale the signal from Amplifier A7 and provides the error signal for integrator I1.

Those skilled in the art will appreciate that there are many modifications that can be made to the embodiments described that are within the spirit and scope of the

invention. For example, shown schematically in Fig. 8 is a portion of an interferometer system which uses two shearing plates, 91 and 93, so that the wavefront shape can be measured along two orthogonal axes simultaneously. In this configuration, the first plate 91 is oriented and rotated by its ThermX drive about one axis, say the vertical, and the second plate is oriented and rotated by its ThermX drive about an orthogonal axis, shown schematically as horizontal axis 95. In this example, light from an optic under test is incident on the first plate, which provides an interference pattern from the light reflected from the front and back surfaces of the plate 91, just as in the prior cases, light which can be detected with a CCD or other device just as shown in Fig. 5. Plate 91, however, is used in transmission, so that a significant portion of the light is transmitted such that it is incident on the second plate 93. Plate 93 then provides an interference pattern for the orthogonal axis which can also be detected just as before. Another approach for measuring the wavefront shape along two orthogonal axes is shown in Fig. 9. In this embodiment, the light incident from the optic under test is incident on an image rotator 1001, which then transmits the light to the interferometer. With this system, one first determines the wavefront shape along one axis, then the image is rotated by 90 degrees by image rotator 1001, and the wavefront shape about an orthogonal axis is determined. Those skilled in the art will also appreciate that the phase shift method described above for determining fringe phase can also be used for a wedged shearing plate as well. Hence, the above analysis can be applied to Fizeau interferometers, and as described in U.S. Patent 4,173,442 (incorporated herein by reference), the laser wavelength can be determined from the fringe phase. Therefore, as an alternative embodiment, the interferometer according to the invention can be used to measure laser wavelength.

There are many other changes as well that could be made to the individual components. For example, the size and material of the etalon can vary widely, the mechanical construction of the base and ring structures may change, and many dimensions can vary. There are many ways that a power and control circuit may be designed to accomplish the purposes of the circuitry of the preferred embodiment for the ThermX drive. An embodiment of the interferometer can also be provided within the spirit and scope of the invention wherein the shearing plate is pivoted to the support and a drive is provided to rotate the shearing plate. Also, those skilled in the art will realize that the choice of using rotations of one-quarter wave was made to simplify calculations. However, there is no intrinsic reason that other angles of rotation could not also be used. Further, there are many different ways the shearing plate may be pivoted in the support, and the drive can similarly take many forms to rotate the plate satisfactorily. For example, a workable drive could incorporate an electric motor and a driven cam engaging a follower on a housing for the shearing plate. There are similarly many other deviations not detailed here that will not deviate from the spirit and scope of the invention, which is limited only by the claims which follow.

Claims:

1. Apparatus for determining characteristics of an incident beam of electromagnetic radiation comprising:

a shearing plate with flat faces, said shearing plate constructed of a transparent material and oriented so as to cause amplitude division by reflection of said incident beam into two parts which are substantially parallel and interfering;

mounting means for supporting said shearing plate; and

movement means coupled to said mounting means for rotating said shearing plate about an axis parallel to one of said faces.

2. Apparatus as in claim 1 further comprising sensing means for determining rotational position of said shearing plate relative to the mounting means.

3. Apparatus as in claim 2 further comprising computer means for controlling said movement means in response to output from said sensing means.

4. Apparatus as in claim 1 further comprising stage means for rotationally holding said mounting means and for measuring angles of rotation of said mounting means.

5. A translator comprising:

a wire having a first end and a second end with a length therebetween;

holding means for attaching said first end and said second end so as to hold said wire under tension;

driver means for changing the temperature of said wire;

sensing means for measuring the resistance of said wire;

feedback means for receiving signals from said sensing

means and for controlling said driver means in response thereto to provide calibrated changes in the length of said wire.

6. Apparatus for determining characteristics of an incident beam of electromagnetic radiation comprising:

a shearing plate with flat faces, said shearing plate constructed of a transparent material and oriented so as to cause amplitude division by reflection of said incident beam into two parts which are substantially parallel and interfering;

mounting means for supporting said shearing plate; and

translation means for rotating said shearing plate relative to the mounting means about an axis parallel to one of said faces, said translation means comprising;

a wire having a first end and a second end with a length therebetween;

holding means for attaching said first end and said second end so as to hold said wire under tension;

driver means for changing the temperature of said wire;

sensing means for measuring the resistance of said wire;

feedback means for receiving signals from said sensing means and for controlling said driver means in response thereto to provide calibrated changes in the length of said wire.

7. Apparatus as in claim 6 further comprising stage means for rotationally holding said mounting means and for measuring angles of rotation of said mounting means.

8. An interferometer comprising:

shearing means for amplitude division by reflection of an incident beam of electromagnetic radiation into two parts

which are substantially parallel, said two parts being displaced relative to each other in a direction transverse to the direction of the incident beam;

mounting means for supporting said shearing means; and

movement means for rotating said shearing means relative to said incident beam about an axis orthogonal to the incident beam.

9. An interferometer as in claim 8 further comprising stage means for rotationally holding said mounting means and for measuring angles of rotation of said mounting means.

10. An interferometer as in claim 8 further comprising fringe sensing means for detecting fringe patterns caused by said shearing means.

11. An interferometer as in claim 10 further comprising computer means for providing a signal to said movement means so as to rotate said shearing means by a plurality of angular increments about said axis.

12. An interferometer as in claim 11 wherein said computer means processes said fringe patterns to determine fringe phase at each increment.

13. An interferometer as in claim 12 wherein said computer means processes said fringe phase at each increment to determine a wavefront phase profile for the incident beam.

14. An interferometer as in claim 10 further comprising computer means for providing a signal to said movement means to cause rotation of said shearing means about said axis, for collecting data from said fringe sensing means which results from rotation of said shearing means about said axis, and for determining wavefront characteristics for the

incident beam from said data.

15. An interferometer system comprising:

shearing means for amplitude division by reflection of an incident beam of electromagnetic radiation into two parts, each part having a wavefront with a direction of propagation that is substantially parallel to the other, said two parts being displaced relative to each other in a direction transverse to the direction of the incident beam so as to cause interference fringes between the two parts;

mounting means for supporting said shearing means and for rotating said shearing means by small amounts about an axis orthogonal to the incident beam.

16. An interferometer system as in claim 15 further comprising fringe sensing means for detecting the interference fringes caused by said shearing means.

17. An interferometer system as in claim 16 further comprising computer means for determining a wavefront profile based on the interference fringes detected by said fringe sensing means corresponding to different angles of orientation and rotation of said shearing means about said axis.

18. An interferometer system as in claim 16 further comprising computer means for processing information from said fringe sensing means to determine a wavefront amplitude profile for said incident beam, thereby determining the complex amplitude of the wavefront of said incident beam.

19. An interferometer system as in claim 18 wherein said computer means Fourier transforms said complex amplitude to determine at least one of the following:

a) far field intensity distribution of the wavefront

for said incident beam;

b) focus spot intensity distribution for said incident beam.

20. An interferometer system as in claim 19 wherein said computer means calculates at least one of the following for the incident beam:

a) M^2;

b) Strehl Ratio.

21. An interferometer system as in claim 16 further comprising computer means for processing information from said fringe sensing means to determine a wavefront phase profile for said incident beam.

22. An interferometer system as in claim 21 wherein said computer means processes said wavefront phase profile to determine at least one of the following characteristics of the incident beam:

a) Zernicke polynomial coefficients;

b) Seidel aberrations.

23. An interferometer as in claim 21 wherein said wavefront phase profile is used to calculate laser wavelength.

24. An interferometer system as in claim 15 wherein said incident beam emanates from an optical system whose optical characteristics are to be determined.

25. An interferometer system as in claim 15 further comprising second shearing means arranged to receive that portion of the electromagnetic radiation from said incident beam that is not reflected by said shearing means, said second shearing means for amplitude division by reflection of said portion into two parts, each part having a wavefront

with a direction of propagation that is substantially parallel to the other, said two parts being displaced relative to each other in a direction transverse to the direction of the incident beam so as to cause interference fringes between the two parts;

second mounting means for supporting said second shearing means and for rotating said second shearing means by small amounts about a second axis, said second axis not being parallel to the axis of rotation of said shearing means nor parallel to the direction of the incident beam.

26. An interferometer system as in claim 15 further comprising image rotation means for rotating said incident beam about its optic axis before said incident beam is incident on said shearing means.

27. An interferometer as in claim 11 wherein said computer mean processes said fringe patterns to determine fringe contrast for each increment.

28. An interferometer as in claim 11 wherein said computer means processes said fringe patterns to determine wavefront amplitude profile.

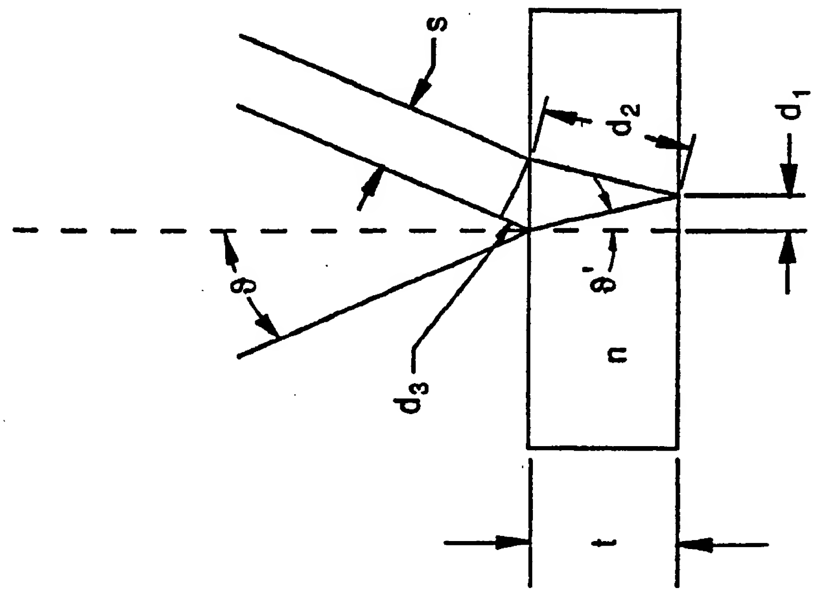
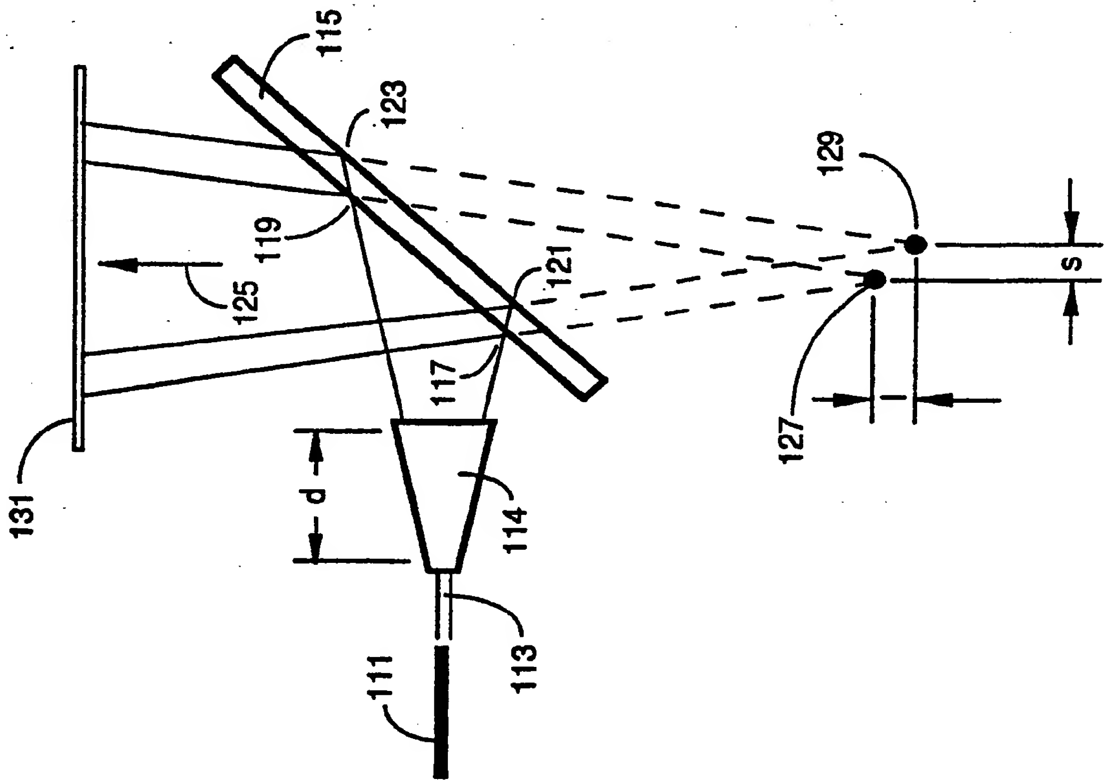

s
d_2
d_1
ϑ
ϑ'
d_3
n
t

Fig. 1B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123
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119
125
121
s
117
127
131
d
114
113
111

Fig. 1A

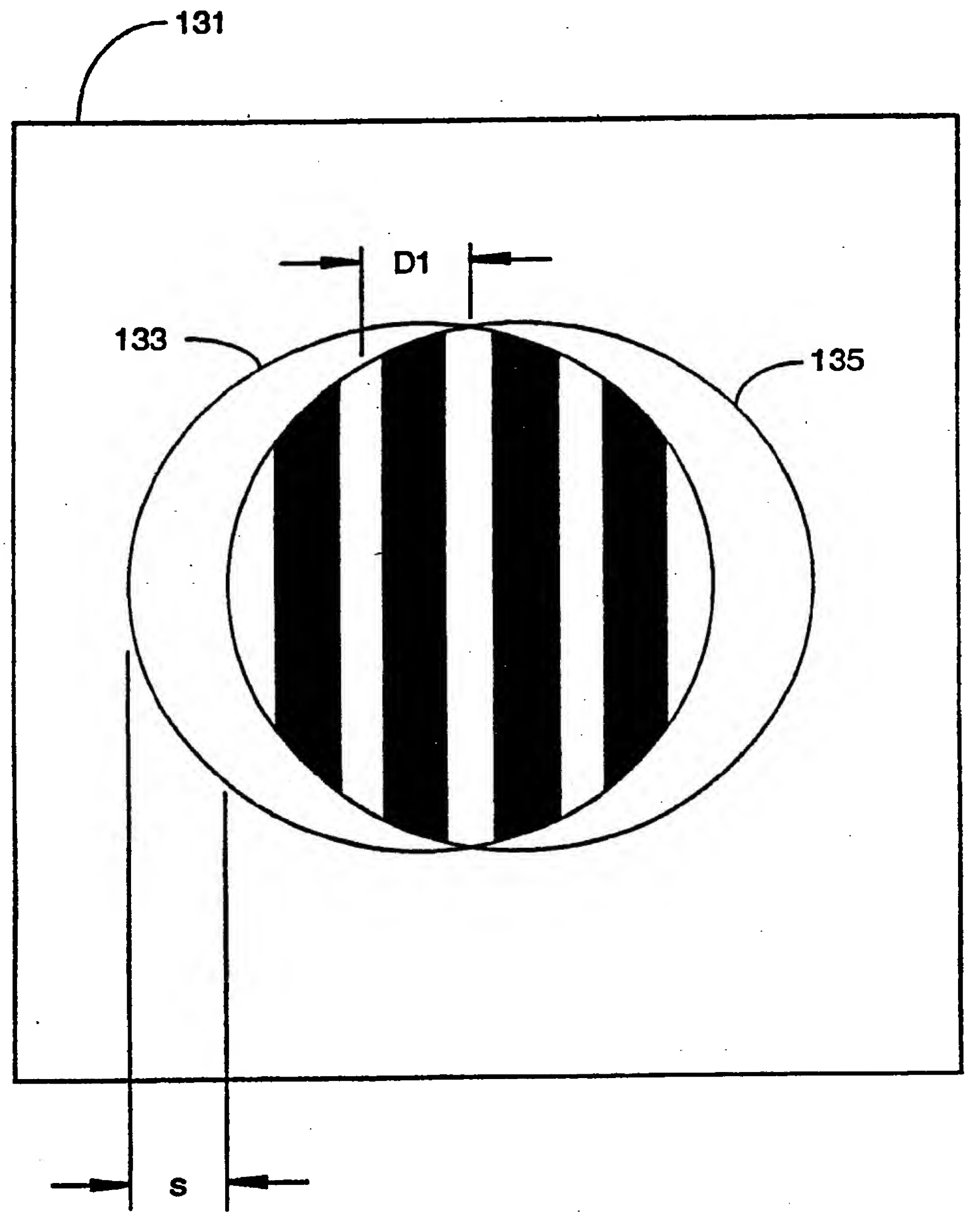


Fig. 2

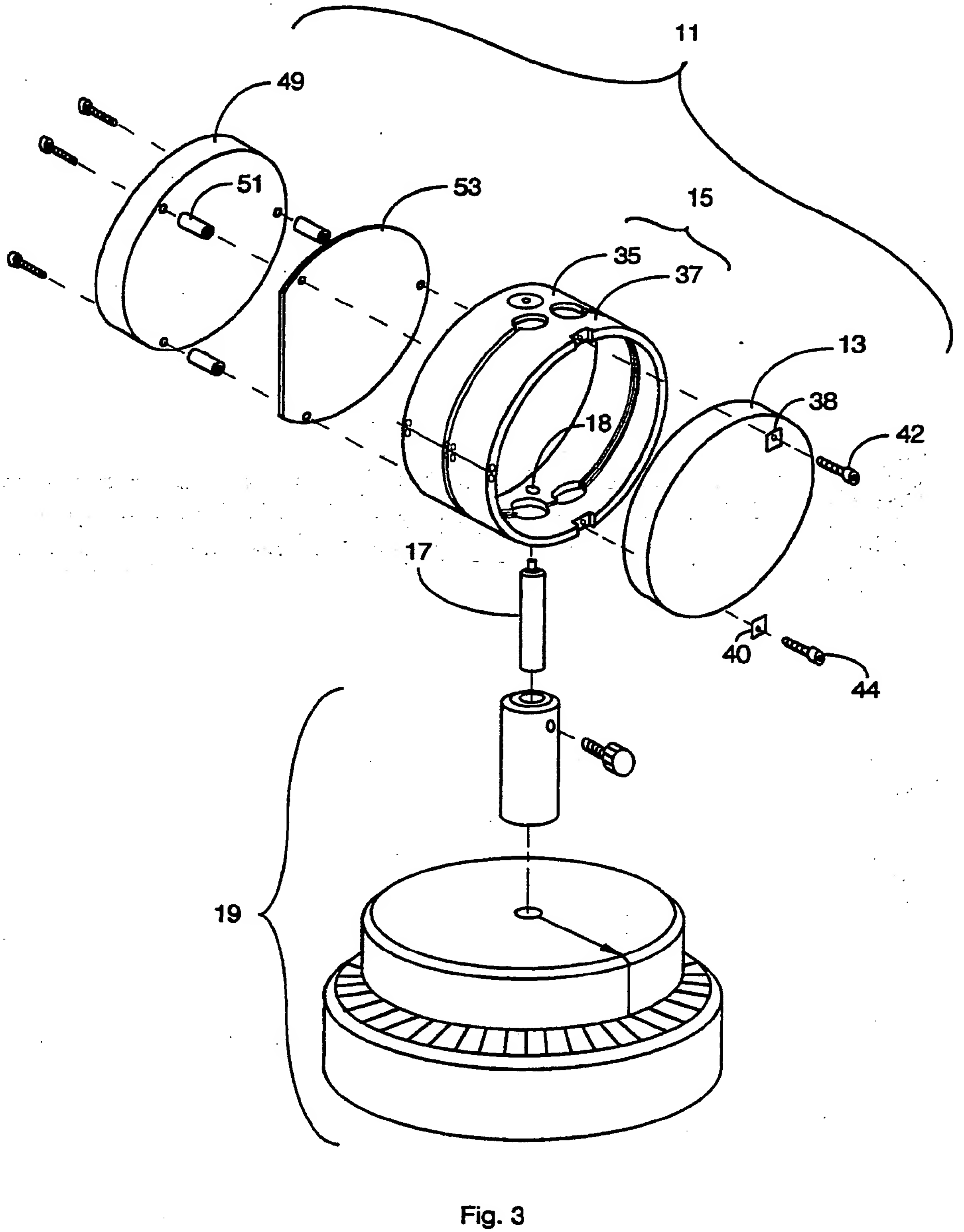


Fig. 3

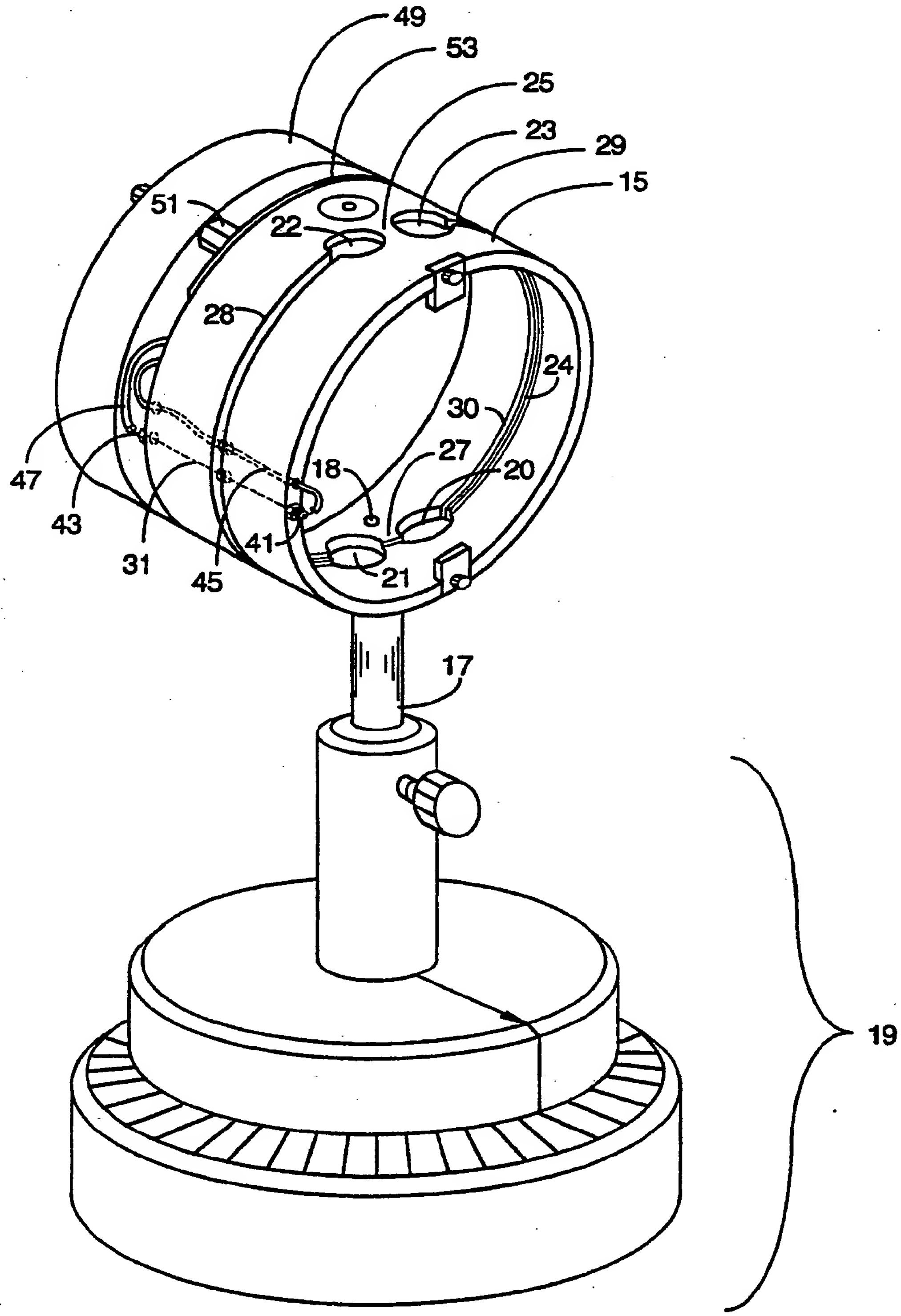
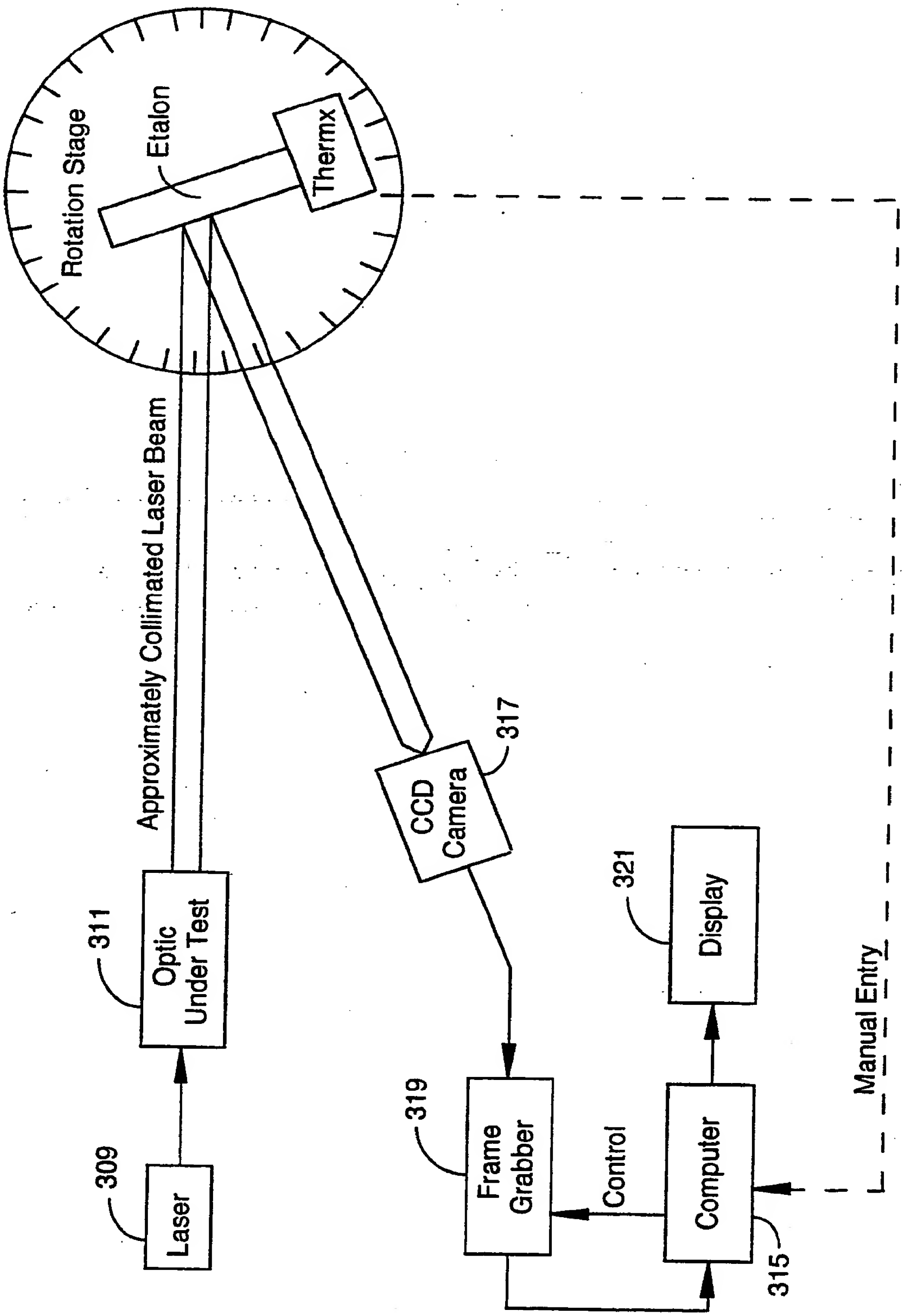


Fig. 4


Rotation Stage
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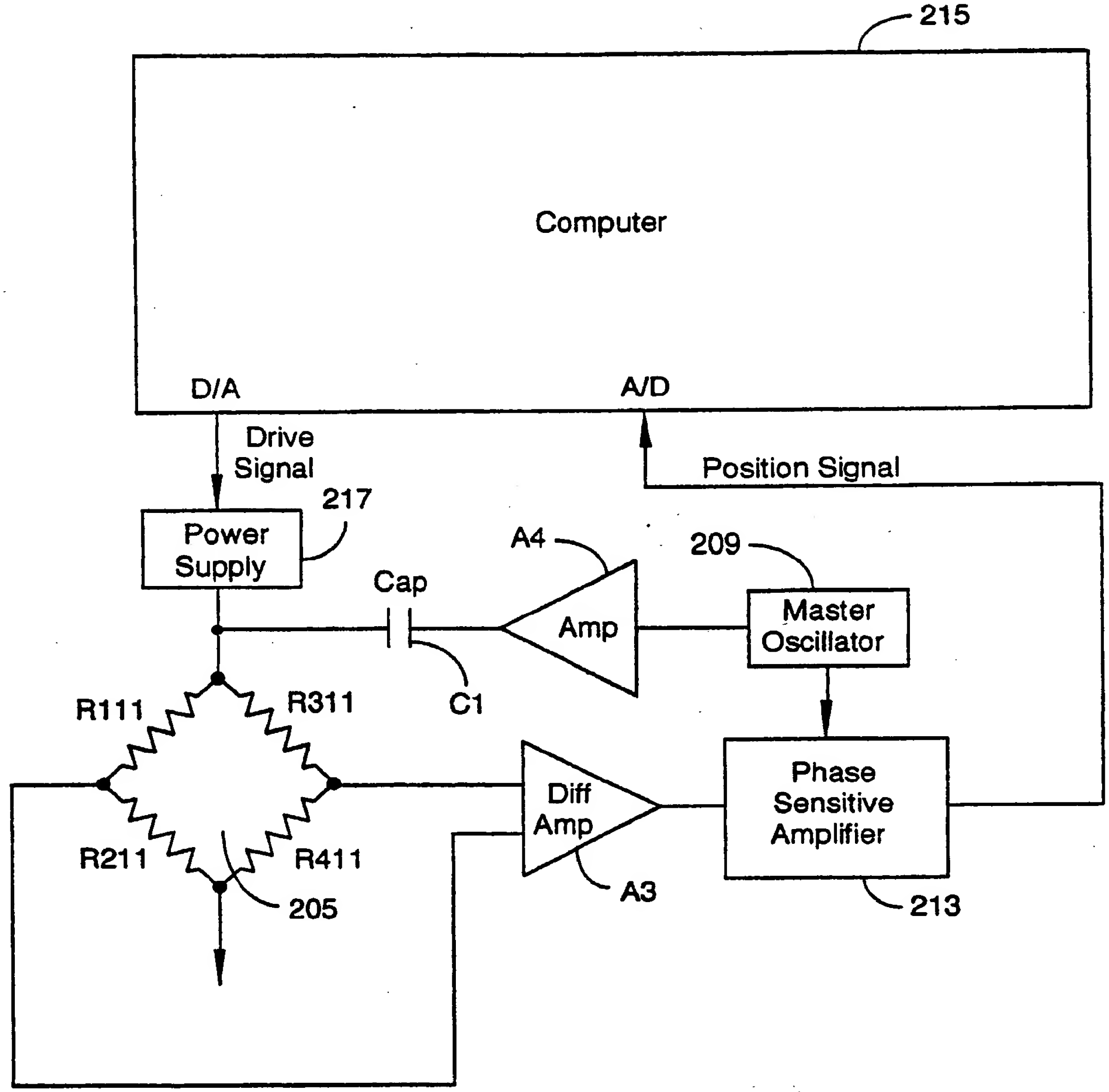
Thermx
Approximately Collimated Laser Beam
CCD Camera
317
Optic Under Test
311
Laser
309
Frame Grabber
319
Control
Computer
315
Display
321
Manual Entry

Fig. 5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A/D
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Position Signal
217
Power Supply
A4
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Cap
Amp
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R311
C1
Phase Sensitive Amplifier
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R411
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A3
213

Fig. 6

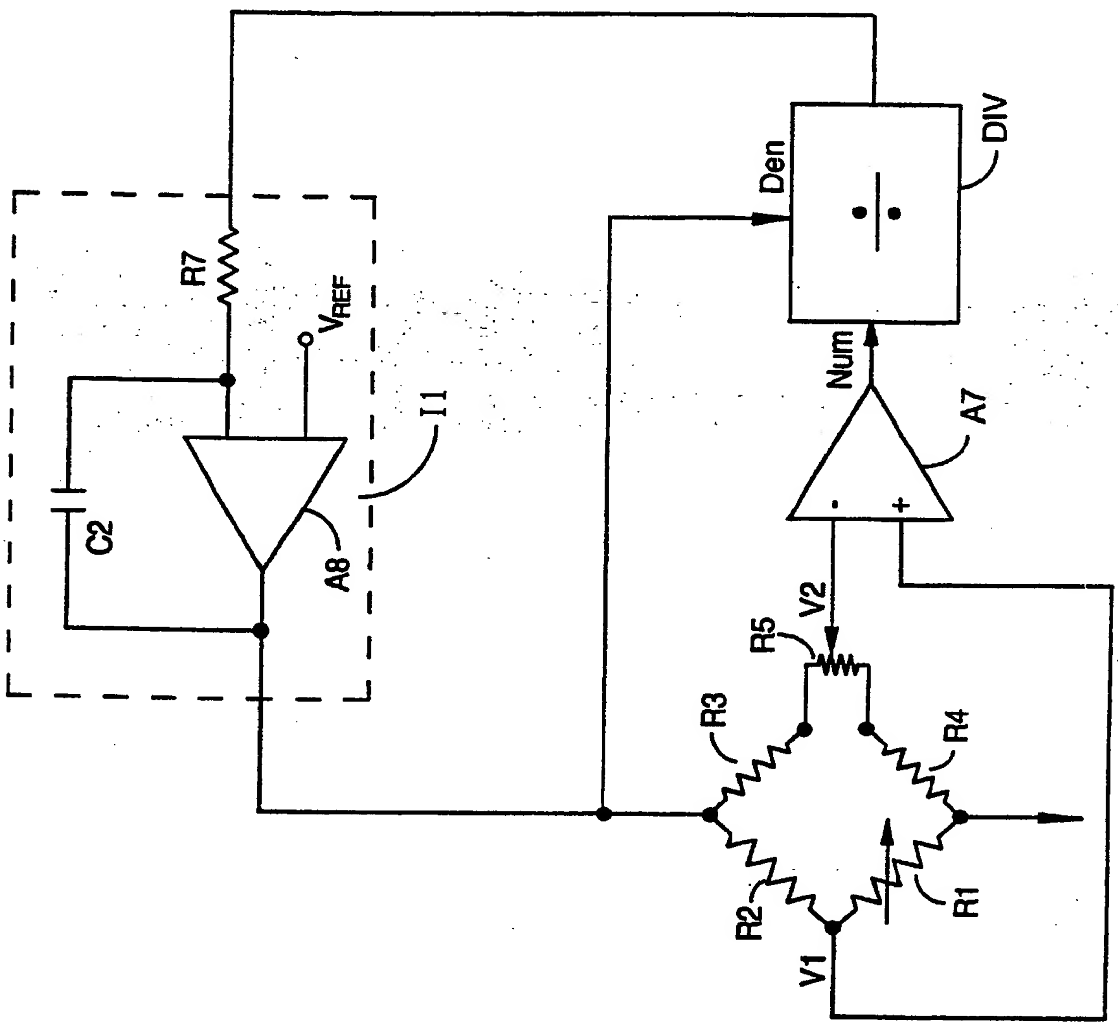

Fig. 7

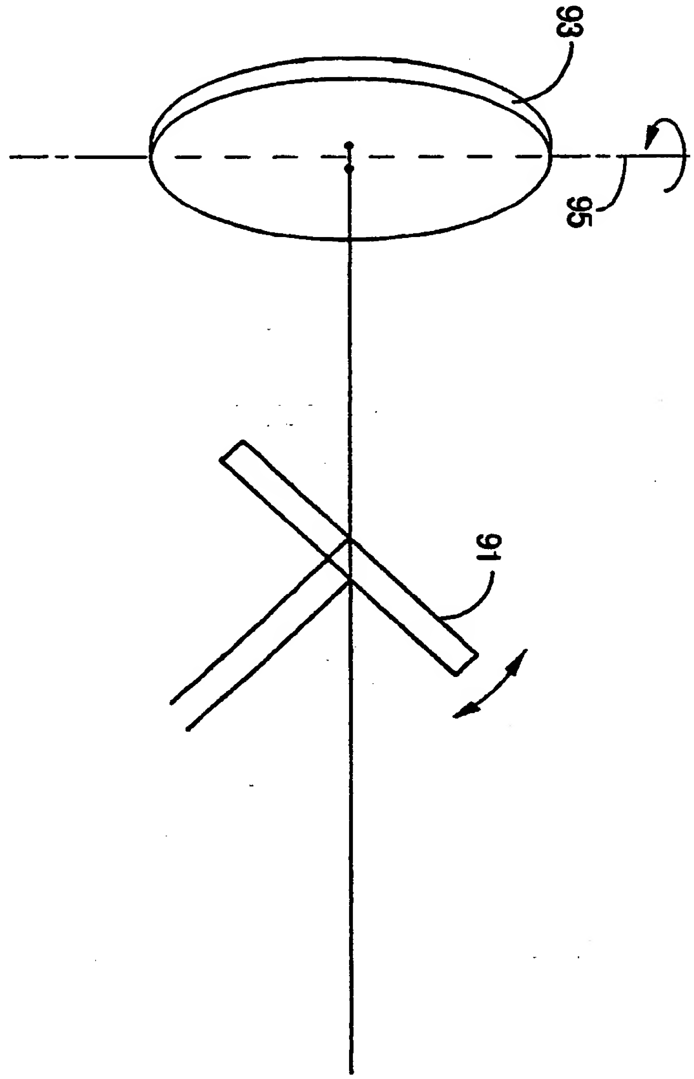

Fig. 8

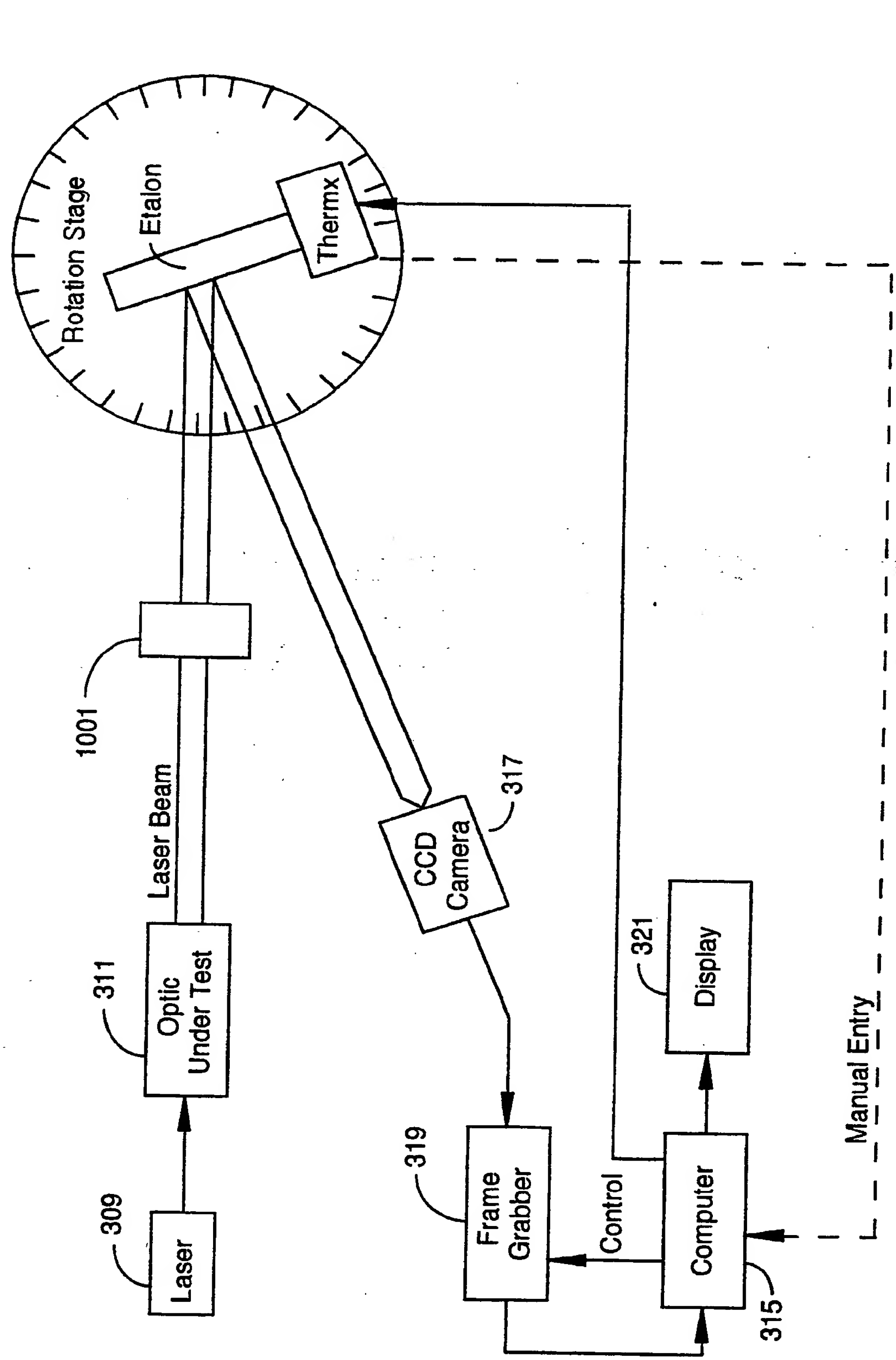
Rotation Stage
Etalon
Thermx
1001
Laser Beam
CCD Camera
317
311
Optic Under Test
309
Laser
319
Frame Grabber
Control
Computer
315
321
Display
Manual Entry

Fig. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US92/04025

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :IPC(5) GO1B 9/02; HO2N 10/00
US CL :356/353; 310/306
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/353; 310/306 356/352, 363; 310/37/307; 318/116, 117,; 60/527,528

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A, 3,229,177 (CLARK) 11 JANUARY 1966 See Figure 2	5,6
A	US,A, 4,786,175 (DUFFUS) 22 NOVEMBER 1988 See Figure 1	1, 6, 8, 15
A	JP,A, 63-50709 (SUZUKI) 03 MARCH 1988 See Figure 1	1.6 8. 15

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 JULY 1992	03 SEP 1992

Name and mailing address of the ISA/ US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	Nguyen Ngoc-Ho For SAMUEL A. TURNER NGUYEN NGOC-HO INTERNATIONAL DIVISION
Facsimile No. NOT APPLICABLE	Telephone No. (703) 308-4803

Form PCT/ISA/210 (second sheet)(July 1992)★

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US92/04025

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Group I, Claims 1-4, 8-28, Drawn to a shearing interferometer, classified in Class 356, subclass 353.

Group II, Claim 5, Drawn to a translator, classified in class 310 , subclass 306.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☒ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any addtional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention frist mentioned in the claims; it is covered by claims Nos.:

Remark on Protest
☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.